

RESULTS OF VISUAL OBSERVATION OF THE NIGHTTIME,
TWILIGHT, AND DAYTIME HORIZON OF THE EARTH
FROM THE "SOYUZ-9" SPACECRAFT

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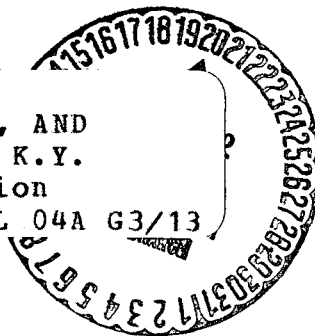
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RESULTS OF VISUAL OBSERVATION OF THE NIGHTTIME,
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ABSTRACT. The characteristic features of the nighttime, twilight, and daytime horizons as observed from "Soyuz-9" are presented, and their possible explanations are discussed.

Visual observations of the Earth's atmosphere from piloted spacecraft are an important part of the optical investigations of the Earth as a planet. Such observations have been made previously by both American and Soviet cosmonauts [1-6]. The successful flight of the "Soyuz-9" spacecraft made it possible for the first time to carry out a wide program of visual and spectrophotometric investigations of the Earth's atmosphere under conditions of a long manned mission in Earth orbit. /574*

This communication presents results of systematic visual observation of the nighttime, twilight, and daytime horizons of the Earth's atmosphere. These observations were made from the "Soyuz-9" spacecraft over various geographic regions of the globe from an average altitude of 220 km, which were typical for the whole period of the mission (April 1-19, 1970).

Nighttime horizon. When the spacecraft is in the Earth's shadow, the ability to observe the nighttime part of the atmosphere is significantly

* Numbers in the margin indicate the pagination in the original foreign text.

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affected by the moonlight conditions. The continents and oceans are quite different in the moonlight; on the continents, the mountains, rivers, and forests can be clearly distinguished. Cloudiness is observed in the form of separate raised inhomogeneities, since the moon illuminates the tops of the clouds. Without moonlight, observational conditions are much worse; in particular, it is impossible to determine the Earth's motion, which makes it difficult to orient the spacecraft.

The basic effect, which is observed visually on the nighttime horizon, is a thin homogeneous luminescent band, which is ashen gray in color with a pinkish hue. This band is uniformly distributed over the Earth's surface in an angular range of about $3^{\circ}40'$. This quantity was precisely defined ($3^{\circ}39'10''$) when the "Soyuz-9" satellite measured the time required for Venus to pass from the middle of the band to the Earth's horizon. There is a very weak haze towards the Earth's surface (below the band). The Earth's horizon is slightly diffused; it is fixed from the moment that a star or a planet sets. The black starry sky could be seen above the band. The optical structure of the band depends on conditions under which the Sun illuminates the atmosphere. A stable correlation is observed between the structure of the band and the angle δ_{\odot} at which the Sun sets behind the horizon. As δ_{\odot} decreases, a stable state is maintained in the neighborhood of a point opposite the Sun. However, the thickness of the band gradually increases at subsolar points, and the band loses its clarity. A fine structure develops in the form of separate fibers in a direction perpendicular to the band. The haze starts to shine below the band near the subsolar point. The haze is distributed to an altitude that is roughly two times the angular height of the band above the horizon. For certain critical values of λ near the subsolar point, the band disappears. At the same time, cosmic dust appears in this region.

Twilight horizon. The beginning of dusk can be seen as a small, dark-red crescent. Then, until the basic color range of the twilight halo forms, illumination starts above the crescent in that part of the atmosphere that

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adjoins the lower part of the halo. After this orange-red and gold tones are added to the dark red tones. The colored band, described above, is simultaneously observed to the right and left of the axis of symmetry of the crescent (in the shadow region). Then the part of the band which is directly next to the crescent on the night side of the atmosphere becomes "separated" (the fine structure of the layer can be seen in the form of separate diverging filaments). As the angle δ_0 is decreased, the region in the sky which is occupied by the colored twilight halo increases. Then it thickens and dominates the washed out discrete structure of that part of the band which adjoins the right and left ends of the halo. The atmosphere below these ends of the band is lightly illuminated. As the angle δ_0 decreases, the red tones in the halo glow, and take on an azure and blue hue. The twilight halo is characterized by the following vertical structure of colored tones from the Earth's surface: red, orange, yellow, pale blue, whitish, again pale blue, again whitish, azure, blue, violet, and black. The first whitish band has a fine structure: it appears to contain two narrow whitish bands, which are separated by a layer which is light blue in color. The second whitish band can be seen at a large distance with infrequent breaks in the horizontal direction. Breaks are observed more frequently in the first whitish band. The distance of the first whitish band from the Earth's surface is roughly $1/3$ of the visible size of the halo. The maximum dimensions of the twilight halo occur just before the Sun rises from behind the horizon. The halo is compressed at the moment when the first solar rays appear; the vertical dimensions suddenly decrease to roughly one third of their initial size.

When the Sun has risen, but the spacecraft is still in the shadow behind the linear terminator, the central part of the region, which was earlier occupied by the halo, loses the colored character described above. The Sun shines on a dark background, but the characteristic illumination of the halo is observed along the direction to the terminator to the right and left of the Sun (right up to the terminator line). However, when the Sun rises farther above the horizon (when the height of the Sun reaches 6 to 15°), an

interesting phenomenon — the "whisker" effect — is observed. Near the terminator the colored halo is torn from the Earth's surface and moves out strictly along a tangent to the region of the black starry heaven at a height of 7 to 9° (about 250 - 300 km). The halo forms a characteristic, symmetrically distributed zone of illumination ("whiskers") with a color range in the vertical direction, which is analogous to the twilight halo. The high-altitude evolution of the colored hues of the dawn remain as before; however, at sunrise the blue-violet part of the halo is compressed. Analogous illumination is also observed at sunset, except that here the vertical dimensions of the yellow-red part of the halo are decreased.

The "whiskers" decay as soon as the terminator is passed.

Daytime horizon. The following characteristic details are observed when the spacecraft passes out of the shadow to the illuminated part of the Earth: The line of the daytime horizon is diffused by a foggy haze. There are no noticeable vertical inhomogeneities in the brightness of the haze. The color of the haze depends on the height of the Sun to a significant degree, and also on the presence of clouds. Thus, above the ocean a cloudy atmosphere near the horizon is colored a dirty-gray tone, but if the atmosphere is free of clouds, then it is a bright blue. The haze color evolution in the vertical direction is simple — from an azure tone (or dirty-grayish) to a blue tone, and then to the black color of space. When the Sun is at the zenith for the observer, then only the haze layer is seen at the horizon, and it is impossible to observe stars in the heaven at that moment. If the Sun is not at the zenith, one window views the continents and the oceans, and the other views the black starry heaven and the moon. The stars are observed in the illuminator opposite from the Sun. The Moon is seen against the black background of space, and the azure band of the Earth's horizon — in the form of a brown sphere with colored spots. The brightness of the haze near the Earth's surface has no effect on the brightness of the Moon. /576

It is interesting to note that it is possible to distinguish the planets and the bright stars, for example Vega (α Lyra), and Spica (α Virgo).

Interpretation and Comparison of Visual Data. The following conclusions can be made from the characteristic visual data presented above. The luminescent band, with split rings in regions next to the twilight halo in the Earth's shadow, was first observed on a planetary scale, although analogous phenomena were noted earlier in space. Thus, for example, J. Glenn [2] observed a local bright layer at an angular height of 6 to 8° above the horizon on the dark side of the Earth; the width of the layer was 1.5 to 2°. This layer could be observed differently during a brief (several seconds) disappearance of the stars when they approach the horizon as the spacecraft moves. The color of the light band, parallel to the horizontal line, was different from the clouds distributed below. This layer was visible on all three orbits of the flight, when the spacecraft was on the night side of the Earth. It was even better observed in the moonlight (although in this case there were no sharply defined regions). There is some doubt about the interpretation of this phenomenon [2] as being due to optical effects in the illuminator glass. The weak luminescent bands on the dark side of the Earth were observed by K. P. Feokistov [5] at a height of about 2.5 to 3° above the edge of the planet in the moonlight. According to the data of D. A. MacDivitt and E. H. White [3], the nighttime horizon in the absence of moonlight is characterized by the presence of three brightness bands: the upper band is an inhomogeneous layer with a cloudy structure, with linear dimensions of the horizontal inhomogeneities ranging from 30 to 300 km; the second (lower) band is significantly dimmer. The third is the weakest, and is difficult to distinguish.

In order to interpret the effect of the band, it is very important to determine the height of this illuminated band above the Earth's surface. Since the angular distance of the band from the Earth's surface was measured accurately, and the height of the "Soyuz-9" spacecraft at the moment of observation was 220 km, then a simple geometric relationship shows that the altitude of the luminescent layer was about 95 km. This altitude is characteristic for the formation of many photochemical and diffusion processes which occur in the upper parts of the Earth's atmosphere. The boundary between the

homogeneous (in chemical composition) and the nonhomogeneous parts of the Earth's atmosphere is approximately at this level. The so-called E-layer of the ionosphere occurs somewhat higher with an increased electron concentration. The height of the E-layer depends on the zenith location of the Sun [7]. Comparing these data on the physics of the upper atmosphere with the above observation leads to the conclusion that the luminescent band is most probably caused by photochemical, recombination, or geomagnetic processes, which occur in the night in a narrow transitional region near this boundary. The most intense luminescent line of the nighttime sky in the spectral region is the line for atomic oxygen ($\lambda = 5577$ and 6300 to 6364 \AA), the D-line of sodium ($\lambda = 5890$ to 5896 \AA), the Meynelovskiy bands of OH and the continuum near $\lambda = 5300 \text{ \AA}$. Results of rocket measurements [8] show that the OI emission ($\lambda = 5777 \text{ \AA}$) is basically focused at an altitude of about 95 km. The sodium emission in the D-lines mainly occurs at altitudes of 75 to 100 km with a maximum at an altitude of about 90 km. The OI line ($\lambda = 6300 - 6364 \text{ \AA}$) illuminates above 160 km, and the Meynelovskiy OH line occurs approximately between 60 and 100 km. Thus it is quite probable that the presence of the band is related to the illumination of the nighttime sky in the continuum near $\lambda = 5300 \text{ \AA}$, with the OI lines ($\lambda = 5577 \text{ \AA}$) or with some sort of corpuscular effect. It is also obvious that this effect can not be explained by sunlight scattered by dust particles of clouds near the Earth, which are supposedly concentrated at a certain altitude above the Earth's surface.

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The color characteristics of the twilight halo most closely correspond to the visual observations of K. P. Feoktistov [5]. It was confirmed that the whitish bands in the lower parts of the twilight halo ("Soyuz-9", "Voskhod") can be interpreted as the remainder of the wide whitish band in a purely molecular atmosphere, to which local aerosol layers have been added (the azure bands between the white ones).

The sharp decrease in the visible dimensions of the halo at the moment that the first rays of the Sun appear at dawn is evidently caused by a physiological visual effect. This effect is related to the brightness

adaptation of human eyes. Actually, when the spacecraft is far from the terminator line in the shadow (large angle of sunset behind the horizon), the direct solar rays illuminate only the upper layers of the atmosphere, where the density is small. As a result the brightness of the light scattered by them is insignificant. On the other hand, when the sunset angle is decreased behind the horizon, all of the denser lower layers are illuminated by direct solar rays. This leads to a significant increase in the brightness of the halo, which reaches a maximum as soon as the Sun moves from behind the horizon. Since the intense scattering of light starts to light the lower layers of the atmosphere more brightly than the higher layers, this appears to the observer as a decrease in the apparent dimensions of the halo in the vertical direction.

We now turn to the effect of the symmetrically distributed colored "whiskers", which are observed when the Sun has already risen from behind the horizon, but when the spacecraft is still behind the terminator line in the shadow. This phenomenon can be explained by the fact that, as the Sun rises, there is an increase in the linear and angular dimensions of the region, occupied by the crescent-shaped twilight halo. However, after the Sun has risen and is above the horizon, but the observer is still in the shadow, the central part of this region is illuminated by intense sunshine and is observed on a background of the bright solar disk as a dark gap. However, the ends of the crescent-shaped zone continue to fulfill the conditions which are characteristic for a developed twilight halo.

The fact that ends of the left and right "whiskers" are found visually behind the terminator line is probably a result of the effects of refraction divergence and multiple scattering. When the spacecraft crosses the terminator line and enters the illuminated part of the planet, the conditions which are necessary for creating the twilight halo are no longer fulfilled. Thus the color range, which is characteristic of the twilight halo, decays, and the surrounding "whiskers" also disappear. The phenomenon of the luminescent

band above the nighttime horizon of the Earth, its luminescent structure under certain illuminating conditions, and the "whisker" effect, which occurs behind the terminator line at high altitudes, can only be fully explained by continuing visual observations and by making additional experiments to determine the vertical profiles of the spectral brightness of the nighttime, twilight, and daytime horizons of the Earth.

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